Lecture 3 - Experimental performance investigation of WECs

Kofoed, Jens Peter

Publication date:
2015

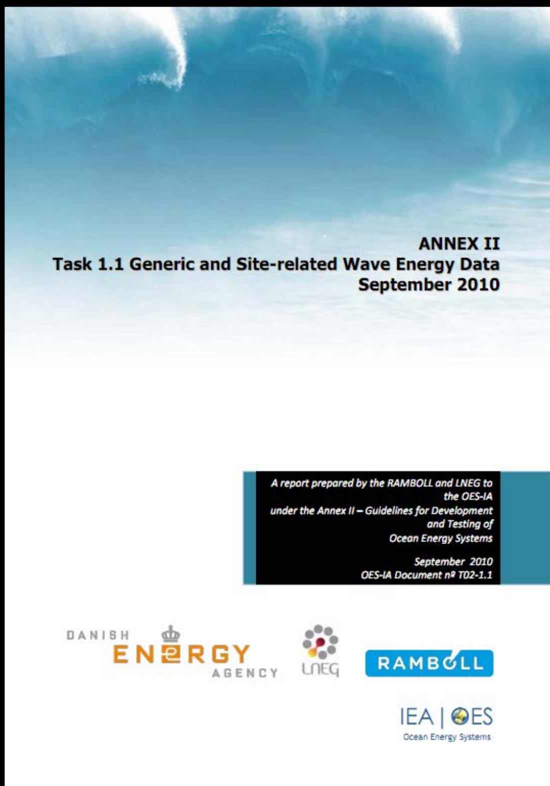
Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

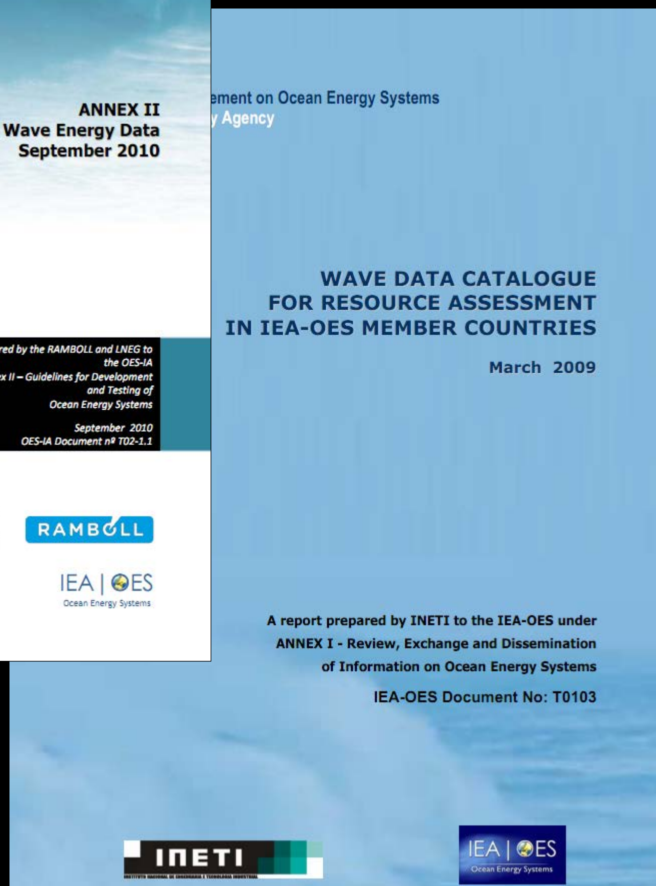
Citation for published version (APA):
Kofoed, J. P. (2015, Aug 25). Lecture 3 - Experimental performance investigation of WECs.

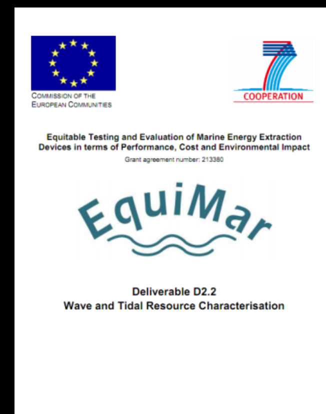
Experimantal performance investigation of wave energy converters

Guidelines and data sources …



www.iea-oceans.org





https://www.wiki.ed.ac.uk/display/EquiMarwiki/EquiMar

TC 114

IEC TC 114 – National 'mirror' committee (DK: DS S-614)

Member based, DK:

- **Aalborg Universitet**
- **Wave Star Energy A/S**
- **Bølgekraftforeningen**
- **Sterndorff Engineering**

PT 62600-1:	**Terminology.**
PT 62600-2:	**Design requirements for marine energy systems.**
PT 62600-10:	**Assessment of mooring system for marine energy converters.**
PT 62600-20:	Guideline for design assessment of Ocean Thermal Energy Conversion (OTEC) system.
PT 62600-30:	Electrical power quality requirements for wave, tidal and other water current energy converters.
PT 62600-40:	Acoustic characterization of marine energy converters.
PT 62600-100:	**Power performance assessment of electricity producing wave energy converters.**
PT 62600-101:	**Wave energy resource assessment and characterization.**
PT 62600-102:	**Wave Energy Converter Power Performance Assessment at a Second Location Using Measured Assessment Data.**
PT 62600-103:	**Wave Tank Testing of Wave Energy Converters.**
PT 62600-200:	Power performance assessment of electricity producing tidal energy converters.
PT 62600-201:	Tidal energy resource assessment and characterization.
PT 62600-202:	Scale testing of tidal stream energy systems.
PT 62600-300:	Electricity producing river energy converters - Power performance assessment.
PT 62600-301:	River energy resource assessment and characterization.

Establish distribution of prevailing wave conditions

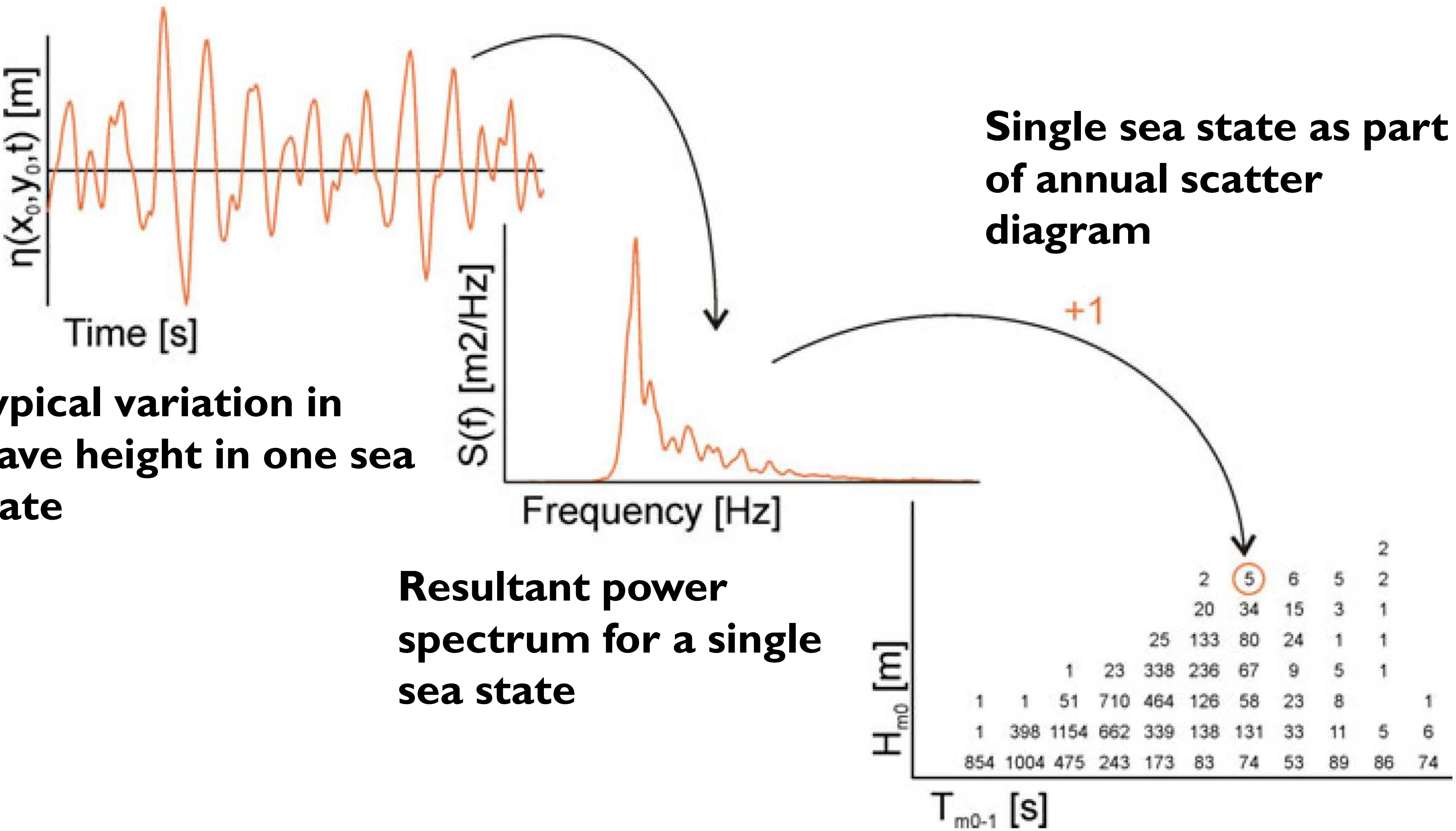
- Sources
  - direct measurements
  - hindcast from wind
  - models, transformation to location
- Parameters
  - significant wave heights
  - peak / energy / average periods
  - wave energy contents
  - direction
  - probability
- Amount of data
  - 20-30 years would be nice to have reliable estimation of average production, but...
  - normally not available directly for location
  - transformation necessary
  - check against shorter term wave measurements

Establishing the scatter diagram

Single sea state as part of annual scatter diagram

Typical variation in wave height in one sea state

Resultant power spectrum for a single sea state



[R. Waters, 2008]

Modeling of wave conditions for energy production

North Sea, Danish Sector (150 km offshore, d= 50 m)

T02 / Hm0	2.0 - 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 6.0	6.0 - 7.0	7.0 - 8.0	8.0 - 9.0	9.0 - 10.0	10.0 - 11.0	11.0 - 12.0	12.0 - 13.0	Sum	%
0.00 - 0.50	460.3	415.2	66.9	19.4	4.6	0.6	0.1					967.1	11.0
0.50 - 1.00	51.9	1520.2	542.4	136.3	46.3	13.8	3.8	0.9	1.9			2317.5	26.4
1.00 - 1.50		239.7	1349.3	138.6	32.5	13.3	6.7	2.4	2.3	0.1		1784.9	20.4
1.50 - 2.00		0.6	689.3	448.5	11.5	3.7	2.1	0.7	0.8	0.4		1157.6	13.2
2.00 - 2.50			20.3	780.8	20.5	1	0.4	0.1	0.1	0.4	0.3	823.9	9.4
2.50 - 3.00			0.4	338.2	214.1	0.3	0.1					553.1	6.3
3.00 - 3.50				17	372.5	1.2						390.7	4.5
3.50 - 4.00				0.3	230.9	34.5						265.7	3.0
4.00 - 4.50					23.7	154.4	0.1					178.2	2.0
4.50 - 5.00					1.2	130.4	0.3					131.9	1.5
5.00 - 5.50						58	21.1					79.1	0.9
5.50 - 6.00						3.8	46.7					50.5	0.6
6.00 - 6.50						0.3	26.7					27	0.3
6.50 - 7.00							15.5	1.9				17.4	0.2
7.00 - 7.50							2	7.3				9.3	0.1
7.50 - 8.00							0.1	6.6				6.7	0.1
8.00 - 8.50								3.1				3.1	0.0
8.50 - 9.00								1.3	0.1			1.4	0.0
9.00 - 9.50								0.1	0.3			0.4	0.0
Sum	512.2	2175.7	2668.6	1879.1	957.8	415.3	125.7	24.4	5.5	0.9	0.3	8765.5	100.0
%	5.8	24.8	30.4	21.4	10.9	4.7	1.4	0.3	0.1	0.0	0.0	100.0	

Modeling of wave conditions for energy production

North Sea, Danish Sector (150 km offshore, d= 50 m)

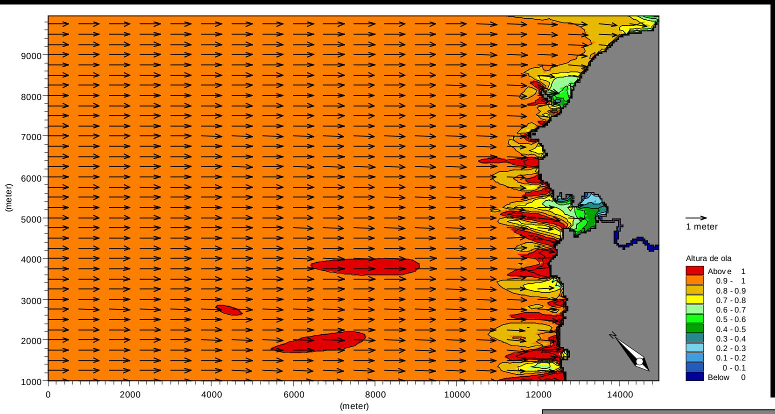
Hm0 \ T02	2.0 - 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 6.0	6.0 - 7.0	7.0 - 8.0	8.0 - 9.0	9.0 - 10.0	10.0 - 11.0	11.0 - 12.0	12.0 - 13.0	Sum	%
0.00 - 0.50	460.3	415.2	66.9	19.4	4.6	0.6	0.1					967.1	11.0
0.50 - 1.00	51.9	1520.2	542.4	136.3	46.3	13.8	3.8	0.9	1.9			2317.5	26.4
1.00 - 1.50		239.7	1349.3	138.6	32.5	13.3	6.7	2.4	2.3	0.1		1784.9	20.4
1.50 - 2.00		0.6	689.3	448.5	11.5	3.7	2.1	0.7	0.8	0.4		1157.6	13.2
2.00 - 2.50			20.3	780.8	20.5	1	0.4	0.1	0.1	0.4	0.3	823.9	9.4
2.50 - 3.00			0.4	338.2	214.1	0.3	0.1					553.1	6.3
3.00 - 3.50				17	372.5	1.2						390.7	4.5
3.50 - 4.00				0.3	230.9	34.5						265.7	3.0
						154.4	0.1					178.2	2.0
						130.4	0.3					131.9	1.5
						58	21.1					79.1	0.9
						3.8	46.7					50.5	0.6
						0.3	26.7					27	0.3
							15.5	1.9				17.4	0.2
							2	7.3				9.3	0.1
							0.1	6.6				6.7	0.1
								3.1				3.1	0.0
								1.3	0.1			1.4	0.0
								0.1	0.3			0.4	0.0
Sum	512.2	2175.7	2668.6	1879.1	957.8	415.3	125.7	24.4	5.5	0.9	0.3	8765.5	100.0
%	5.8	24.8	30.4	21.4	10.9	4.7	1.4	0.3	0.1	0.0	0.0	100.0	

Hs = 1.0 m Tz=4.0 s
Hs = 2.0 m Tz=5.0 s
Hs = 3.0 m Tz=6.0 s
Hs = 4.0 m Tz=7.0 s
Hs = 5.0 m Tz=8.0 s

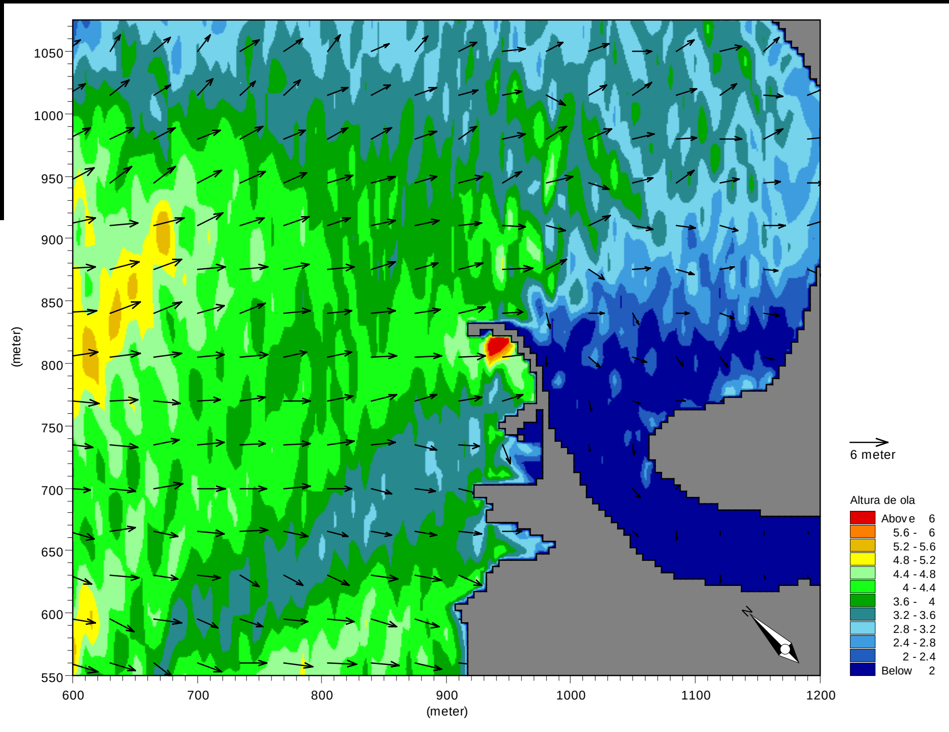
11.0
46.8
22.6
10.8
5.1
2.4
1.3

Sea State	Hs	Tz	Tp	Energy flux	Prob. Occur.
	m	*sec*	*sec*	*kW/m*	*%*
1	1.0	4.0	5.6	2.1	46.8
2	2.0	5.0	7.0	11.6	22.6
3	3.0	6.0	8.4	32.0	10.8
4	4.0	7.0	9.8	65.6	5.1
5	5.0	8.0	11.2	114.0	2.4

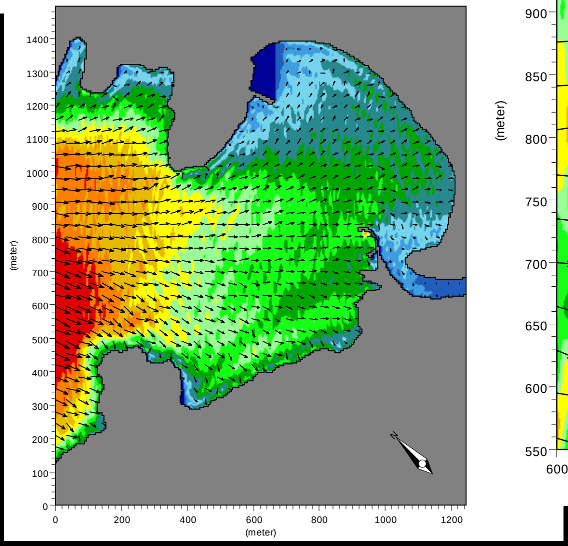
Transformation of waves from offshore to near/onshore



Numerical wave transformation modelling



- WAN – deep water / SWAN - shallow water
- MIKE21 Model
- *WAVEWATCH III*
- *MILDwave*
- *Tomawac*



Design waves

Extreme conditions

- 50 years event often used (corresponding to a 2 % exceedence probability pr. year)
- In phase 1 tests often only qualitative observations used
- In phase 2 extreme conditions are reproduced using 1-2.000 waves. Dimensioning load often taken as F1/250

North Sea, Danish Sector

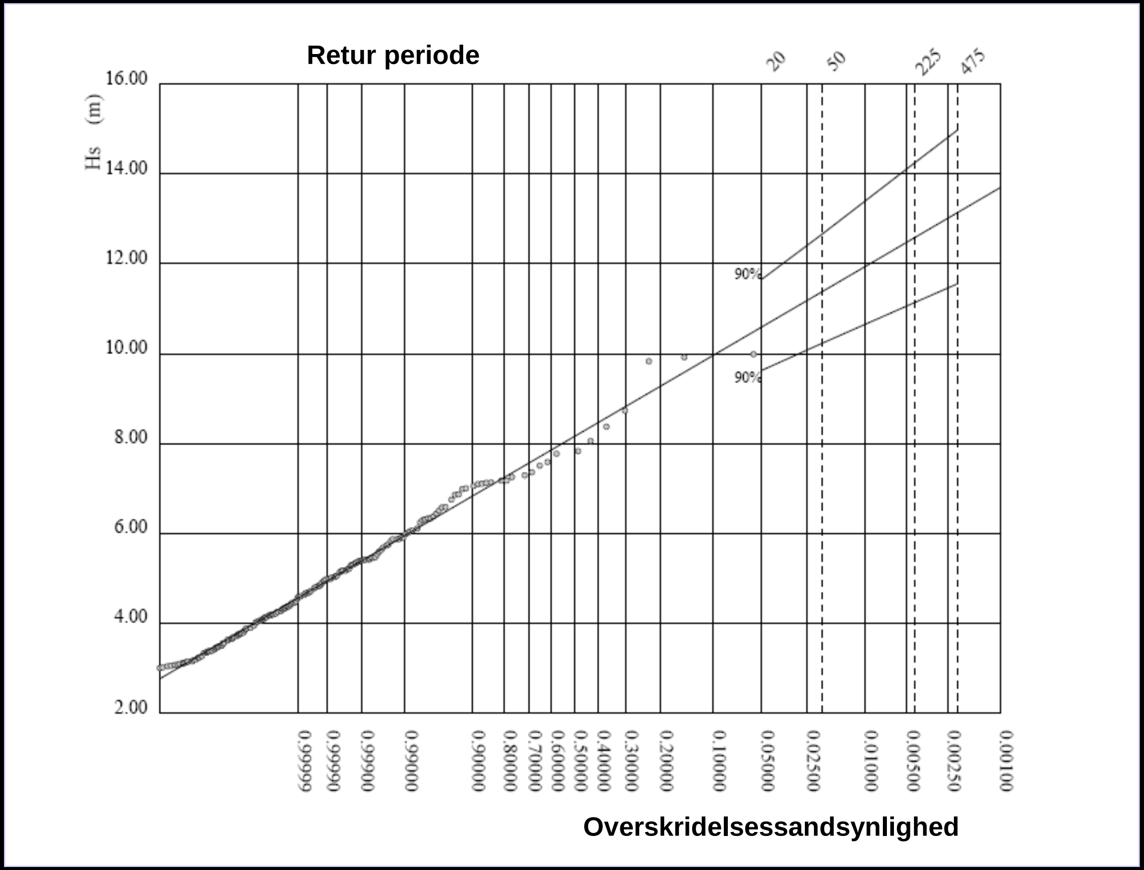
Sea State	Hs	Tz	Tp	Return Period
	m	*sec*	*sec*	*years*
D10	8.0	9.4	13.1	10
D50	9.0	9.9	13.8	50
D100	10.0	10.4	14.5	100

Sea state	1	2	3	4	5	
Hs (m)	1	2	3	4	5	6-10
H (m)	0.7	1.4	2.1	2.8	3.5	4.2-7.1
N [$\cdot 10^4$]	450	170	71	25	7.5	2.0

Fatigue

- Often not considered at phase 1 and 2

Statistics of extreme events



Again – wave transformation might be necessary

How to get performance data?

- The straight way is full scale experience… normally not an option!

- We need model testing and/or numerical modelling

What is a physical model?

- A physical system reproduced (at reduced size) so dominant forces are represented in the model in correct proportion to the prototype

Why model tests?

- Seek qualitative insight
- Obtain measurements to check theoretical results
- Obtain measurements to validate/calibrate numerical results
- Obtain measurements of phenomena too complicated for theoretical/numercal evaluation

Dimensional analysis

- Dimensional analysis is a rational procedure for combining physical variables into dimensionless products, and thereby reducing the number of variables that need to be considered.
- Steps:
  - 1. Identify <u>independent</u> variables
  - 2. Select dependent variable
  - 3. Establish possible independent dimensionless products
  - 4. Reduce system var. to the proper number of independent dimensionless variables

Buckingham Pi theorem

”In a dimensionally homogeneous equation involving ’n’ variables, the number of dimensionless products that can be formed from ’n’ variables is ’n-r’, where ’r’ is the number of fundamental dimensions (L T M) encompassed by the variables”

$$x_1 = f\left(x_2, x_3, \ldots, x_n\right)$$

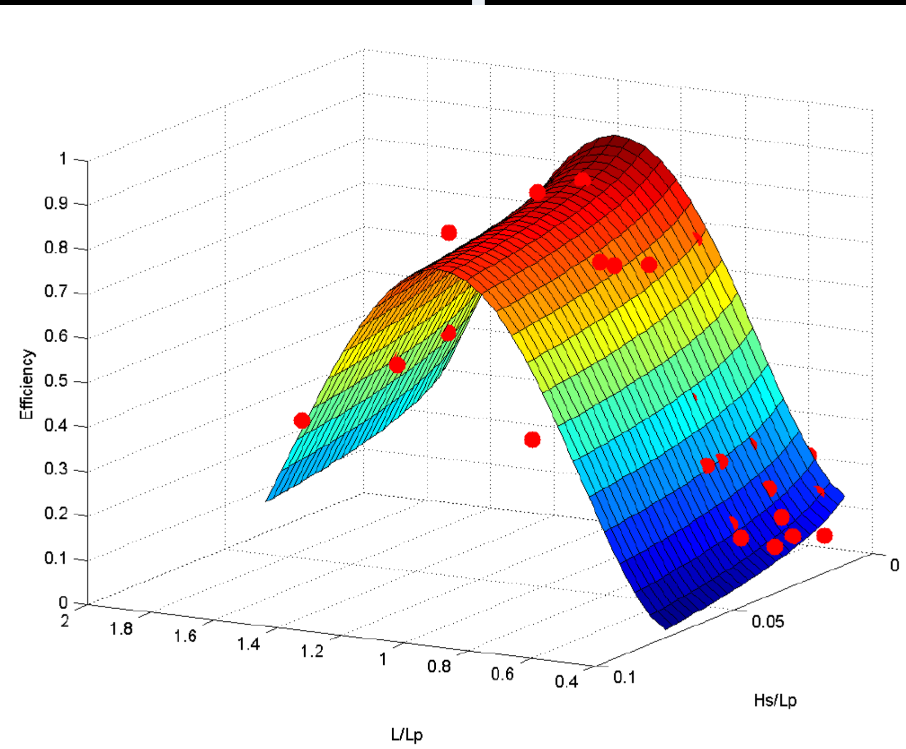
$$\Downarrow$$

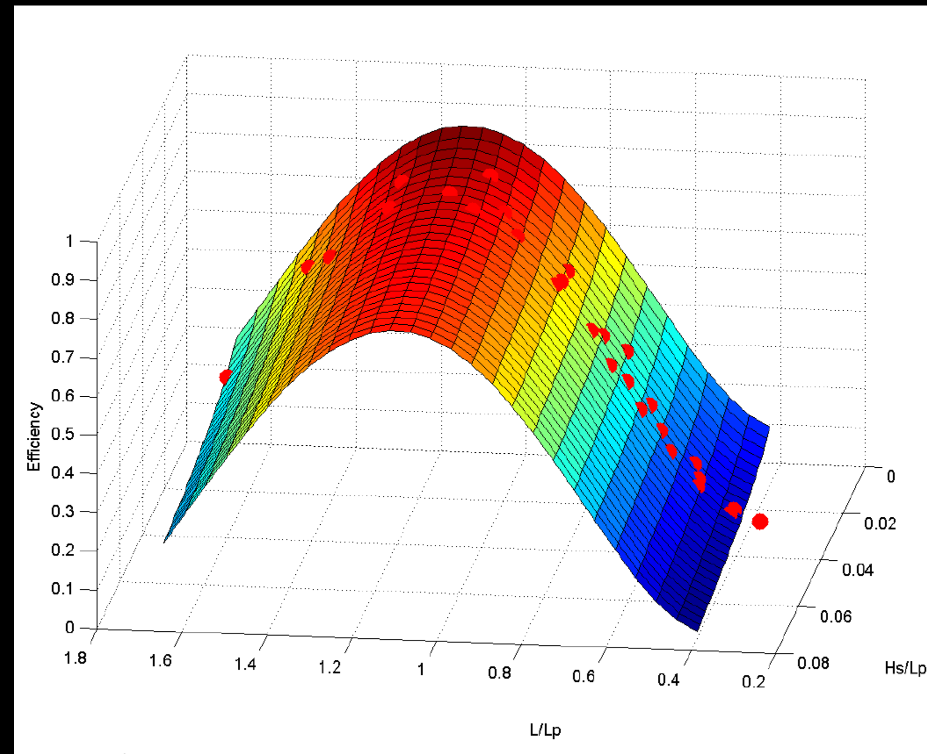
$$\Pi_1 = \Psi\left(\Pi_2, \Pi_3, \ldots, \Pi_{n-r}\right)$$

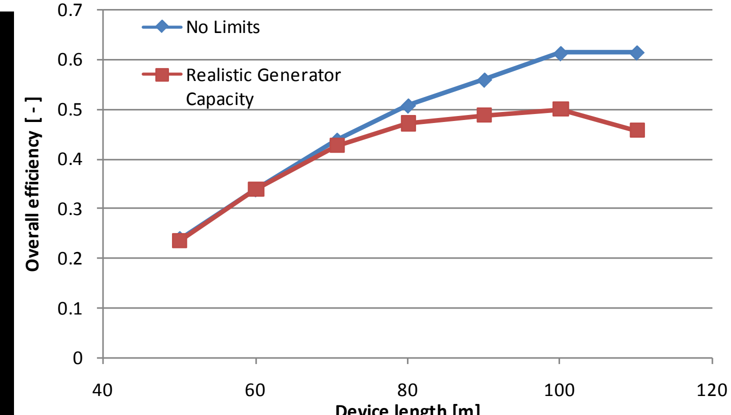
<u>if</u> all original variables appear at least once in one of the dimensionless products

Physical model tests can then be used to establish correlations between these dimensionproducts

An example


Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
L/Lp
0
0.05
0.1
Hs/Lp


Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
L/Lp
0
0.02
0.04
0.06
0.08
Hs/Lp


No Limits
Realistic Generator Capacity
Overall efficiency [-]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
40
60
80
100
120
Device length [m]

Principles of similitude – scaling laws

- To ensure similitude between prototype and model, the following requirements must be met:
  - Geometric similarity – ratio between dimensions constant [L]
  - Kinematic similarity – ratio between motions constant [L T]
  - Dynamic similarity – ratio between forces constant [L T M]

- Impossible for ALL forces. Evaluation of violations necessary – these are the scale effects.

Scaling criteria

- **Froude – gravity**
- Reynolds – viscous
- Weber – surface tension
- Gauchy – elasticisity
- Euler – pressure coef.

Characteristic	Dimension	Froude	Reynolds
Geometric			
Length	$[L]$	N_L	N_L
Area	$[L^2]$	$N_L{}^2$	$N_L{}^2$
Volume	$[L^3]$	$N_L{}^3$	N_L^3
Kinematic			
Time	$[T]$	$N_L^{1/2} N_\rho^{1/2} N_\gamma^{-1/2}$	$N_L^2 N_\rho N_\mu^{-1}$
Velocity	$[LT^{-1}]$	$N_L^{1/2} N_\rho^{-1/2} N_\gamma^{1/2}$	$N_L^{-1} N_\rho^{-1} N_\mu$
Acceleration	$[LT^{-2}]$	$N_\gamma N_\rho^{-1}$	$N_L^{-3} N_\rho^{-2} N_\mu^2$
Discharge	$[L^3T^{-1}]$	$N_L^{5/2} N_\rho^{-1/2} N_\gamma^{1/2}$	$N_L N_\rho^{-1} N_\rho$
Kinematic Viscosity	$[L^2T^{-1}]$	$N_L^{3/2} N_\rho^{-1/2} N_\gamma^{1/2}$	$N_\rho^{-1} N_\mu$
Dynamic			
Mass	$[M]$	$N_L^3 N_\rho$	$N_L^3 N_\rho$
Force	$[MLT^{-2}]$	$N_L^3 N_\gamma$	$N_\rho^{-1} N_\mu^2$
Mass Density	$[ML^{-3}]$	N_ρ	N_ρ
Specific Weight	$[ML^{-2}T^{-2}]$	N_γ	$N_L^{-3} N_\rho^{-1} N_\mu^2$
Dynamic Viscosity	$[ML^{-1}T^{-1}]$	$N_L^{3/2} N_\rho^{1/2} N_\gamma^{1/2}$	N_μ
Surface Tension	$[MT^{-2}]$	$N_L^2 N_\gamma$	$N_L^{-1} N_\rho^{-1} N_\mu^2$
Volume Elasticity	$[ML^{-1}T^{-2}]$	$N_L N_\gamma$	$N_L^{-2} N_\rho^{-1} N_\mu^2$
Pressure and Stress	$[ML^{-1}T^{-2}]$	$N_L N_\gamma$	$N_L^{-2} N_\rho^{-1} N_\mu^2$
Momentum, Impulse	$[MLT^{-1}]$	$N_L^{7/2} N_\rho^{1/2} N_\gamma^{1/2}$	$N_L^2 N_\mu$
Energy, Work	$[ML^2T^{-2}]$	$N_L^4 N_\gamma$	$N_L N_\rho^{-1} N_\mu^2$
Power	$[ML^2T^{-3}]$	$N_L^{7/2} N_\rho^{-1/2} N_\gamma^{3/2}$	$N_L^{-1} N_\rho^{-2} N_\mu^3$

Model laws and scaling

Froudes Model law:

- Inertia forces are dominating. These are proportional to the volume/mass of the device.
- Friction forces are neglegible.
- Geometrical similar with full scale device.

Choice of scaling ratio:

- Measuring accuracy ⇒ model size ↑
- Ratio between friction and inertia forces ⇒ model size ↑
- Surface tension ⇒ model size ↑
- Modelling of PTO system ⇒ model size ↑
- Handability ⇒ model size ↓
- Time restrictions ⇒ model size ↓
- Available laboratory size ⇒ model size ↓
- Economics ⇒ model size ↓

Parameter	Model	Full Scale	Example 1:100
Length	1	S	100
Area	1	S^2	10000
Volume	1	S^3	1000000
Time	1	$S^{0.5}$	10
Velocity	1	$S^{0.5}$	10
Force	1	S^3	1000000
Power	1	$S^{3.5}$	10000000

⇒ Scaling ratios of 1:25 – 40 often used in our lab. (1 W ~ 80 – 400 kW !!!)

Measuring techniques – an overview

Measurements of:

- waves (surface elevations)
- pressures
- Forces (strain / stress)
- Motions (displacements / velocity / accelerations)
- Flow
- Torque
- Current velocity
- Dimensions
- ***

Wave (surface elevation) measurements

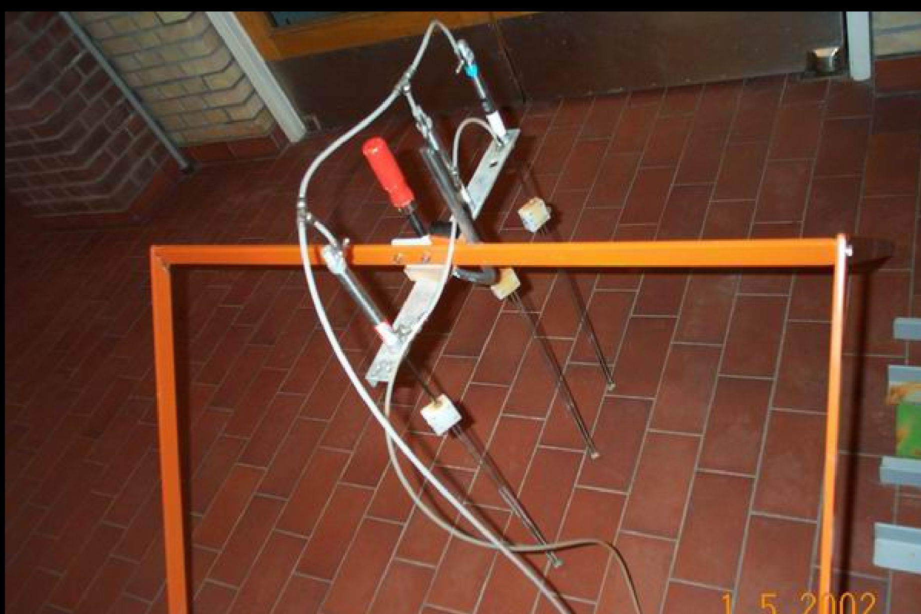
Resistance gauge

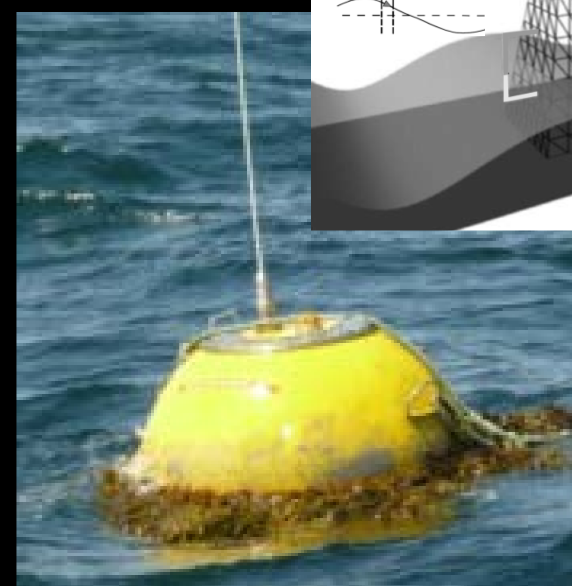
- Lab., also for run-up

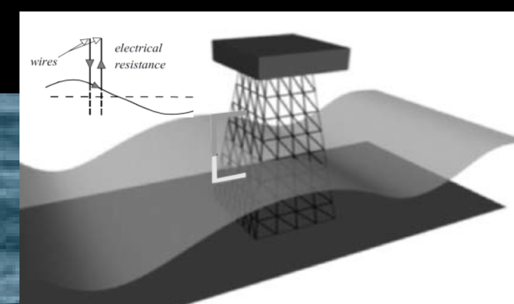
Capacitance gauge

- Sea water ok

- 3D arrays
  - for 3D wave analysis
- Wave rider buoy
  - Point or 3D wave data







Wave (surface elevation) measurements

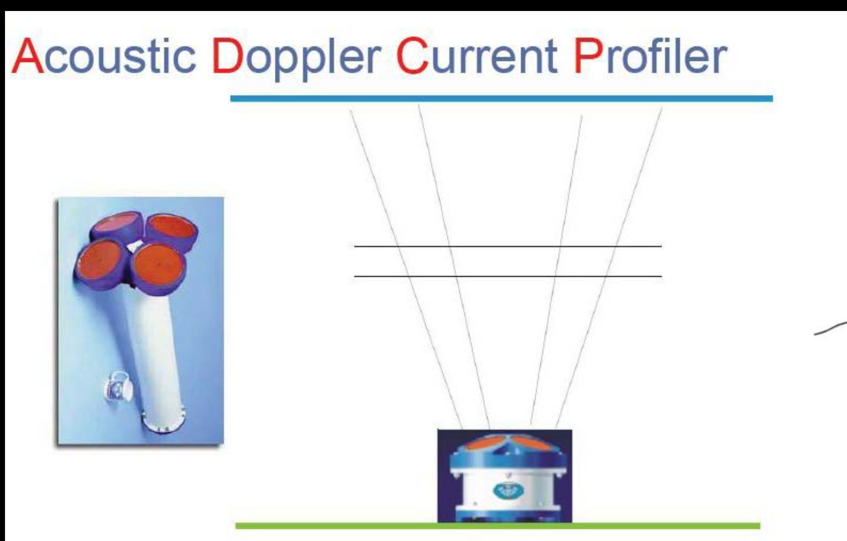
ADCP

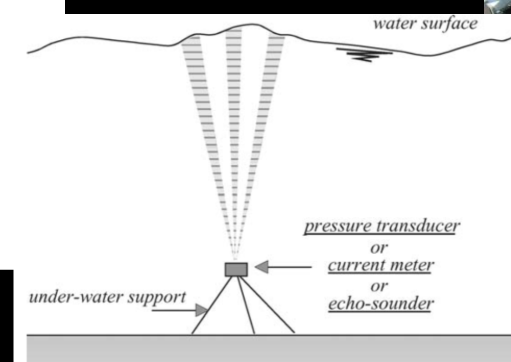
- Sea, also 3D data

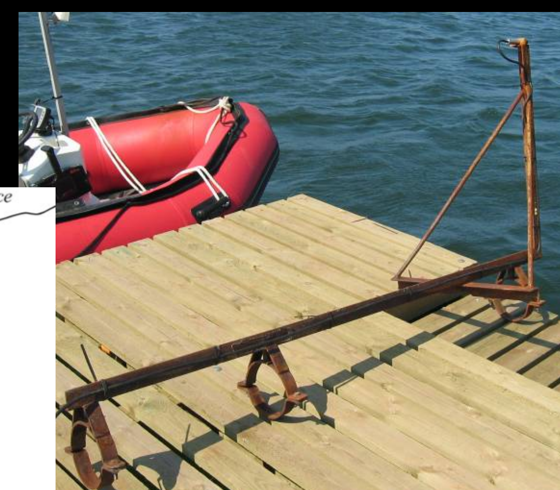
Radar

- Sea, point, need structure

- Step gauge
  - Lab. or sea, good for run-up
- Pressure transducer
  - Primarely sea, cheap, data needs transformation



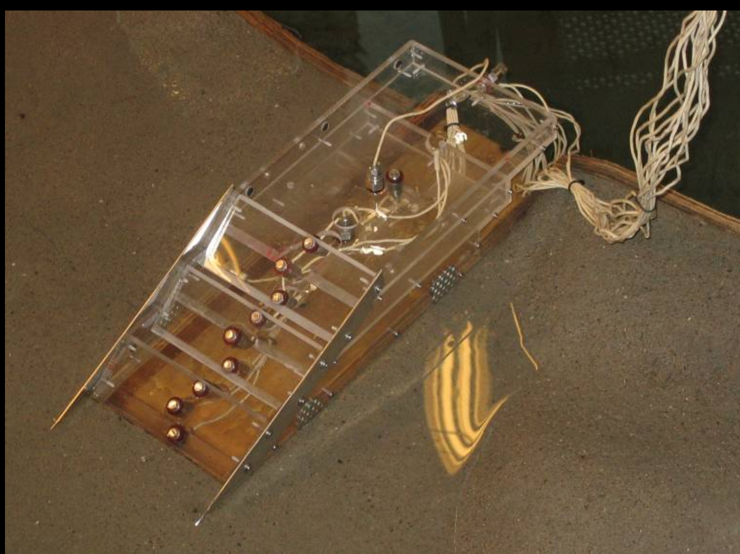


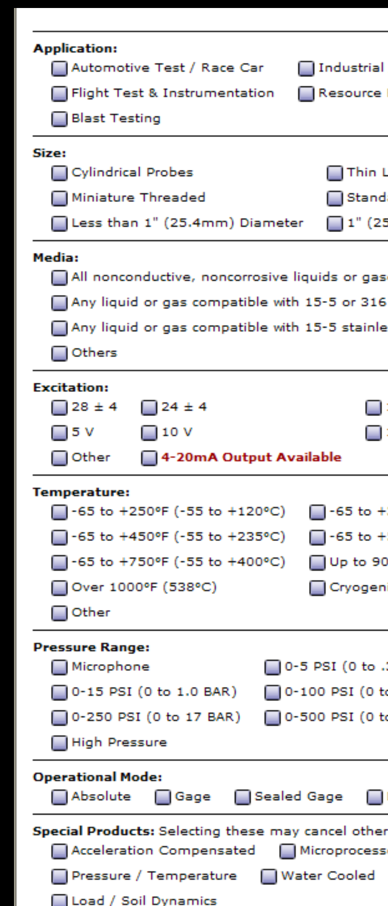


Pressure Measurements

Pressure transducers / transmitters

- Lab and real sea
- Various sizes shapes





Application:
- Automotive Test / Race Car
- Industrial
- Flight Test & Instrumentation
- Resource
- Blast Testing

Size:
- Cylindrical Probes
- Thin L
- Miniature Threaded
- Standa
- Less than 1" (25.4mm) Diameter
- 1" (25

Media:
- All nonconductive, noncorrosive liquids or gase
- Any liquid or gas compatible with 15-5 or 316
- Any liquid or gas compatible with 15-5 stainle
- Others

Excitation:
- 28 ± 4
- 24 ± 4
- 5 V
- 10 V
- Other
- 4-20mA Output Available

Temperature:
- -65 to +250°F (-55 to +120°C)
- -65 to +
- -65 to +450°F (-55 to +235°C)
- -65 to +
- -65 to +750°F (-55 to +400°C)
- Up to 90
- Over 1000°F (538°C)
- Cryogeni
- Other

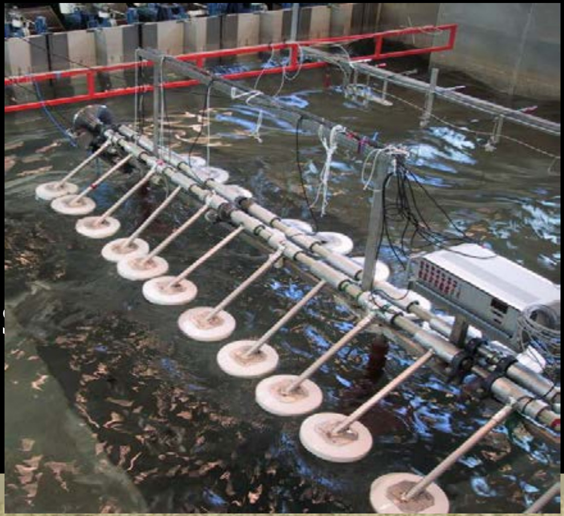
Pressure Range:
- Microphone
- 0-5 PSI (0 to .
- 0-15 PSI (0 to 1.0 BAR)
- 0-100 PSI (0 to
- 0-250 PSI (0 to 17 BAR)
- 0-500 PSI (0 to
- High Pressure

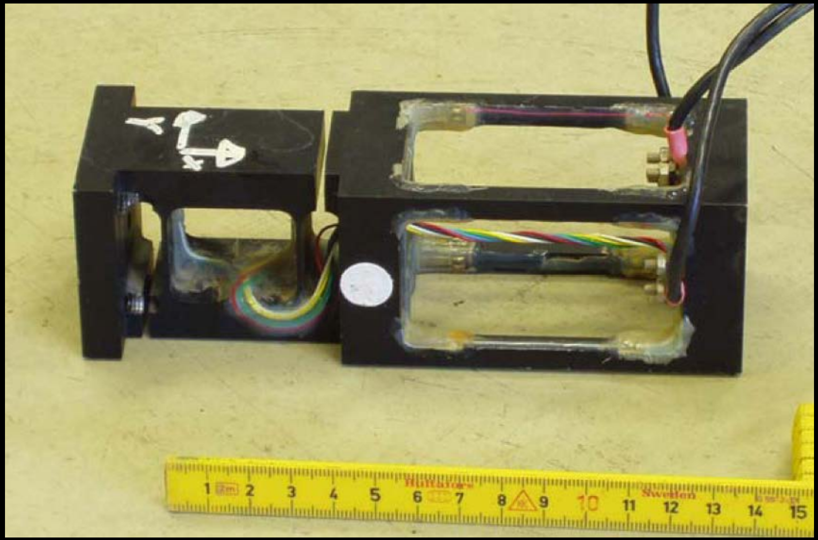
Operational Mode:
- Absolute
- Gage
- Sealed Gage

Special Products: Selecting these may cancel other
- Acceleration Compensated
- Microprocess
- Pressure / Temperature
- Water Cooled
- Load / Soil Dynamics

Forces (strain / stress) - laboratory

- Frame with displacement gauge
- "Bone" with SG's
- Tension/compression transducer
- SG's on structure
- Real sea: Mechanical protection!
- Quarter/half/full bridge configurations

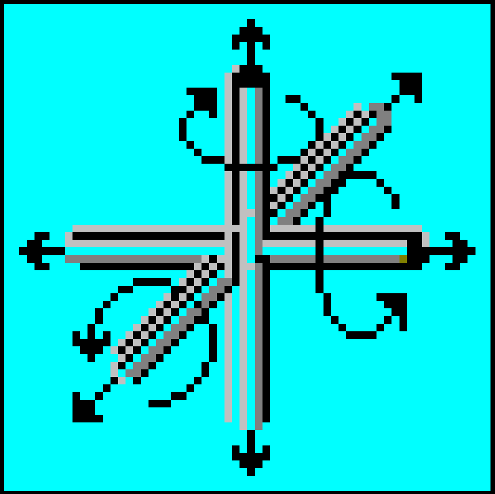




Forces (strain / stress) - sea

- Tension/compression transducer
- SG's on structure

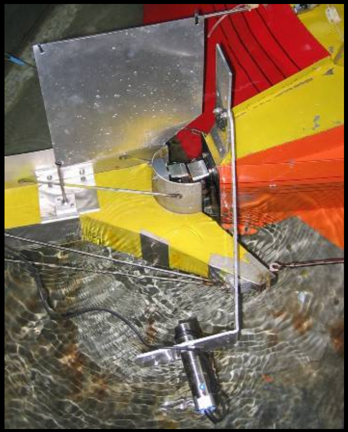
Motions (displacements / velocity / accelerations)

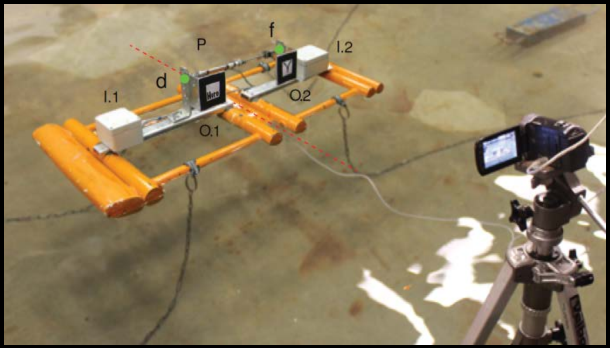


6 DOF rigid body motions

- Translation: Heave, surge, sway
- Rotation: Pitch, roll, yaw

- Wire / potentiometer
- Ultrasonic/laser remote sensing
- Camera based sensing
- Accellerometers (IMUs)

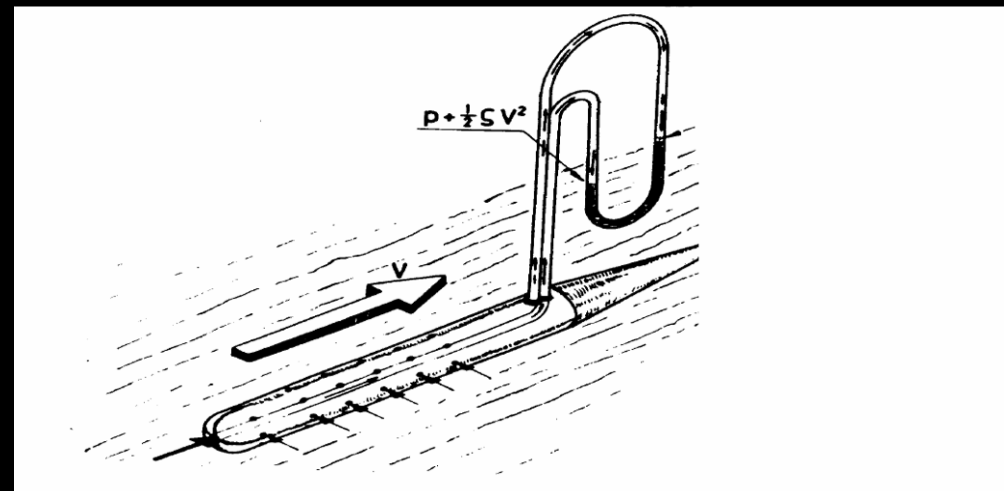


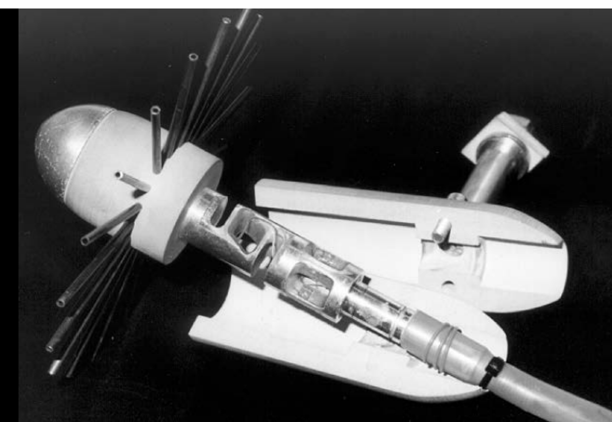


Flow

$$P = Q(\tfrac{1}{2}\rho v^2 + \rho g h + \Delta p)$$

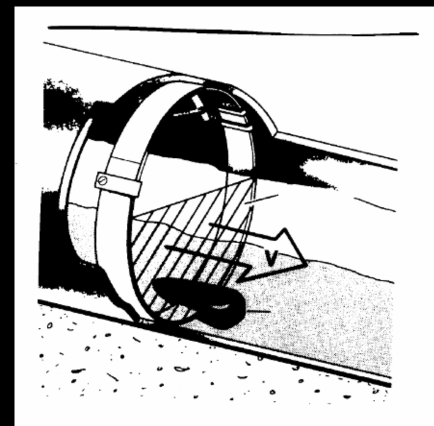
- Ultrasonic (Doppler)
- Pitot pipe
- Turbine flow meter
- Pressure and moment

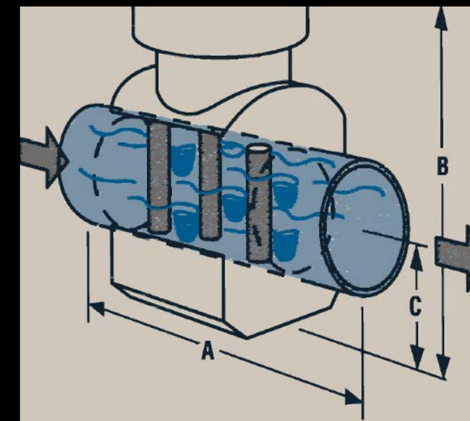


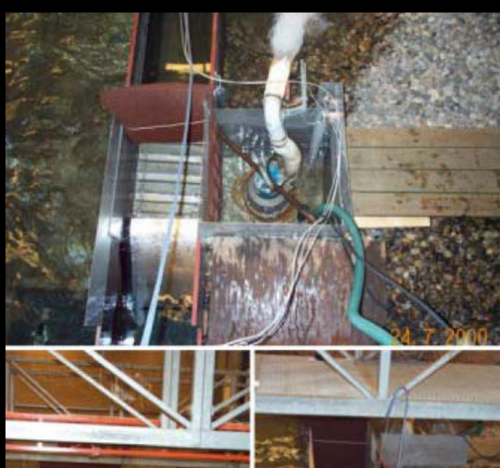


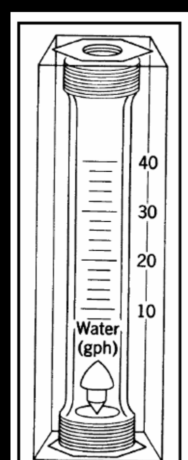
Flow

- Electromagnetic field
- Rotameter
- Vortex flow meter
- Head loss over orifice
- Flow over vier
- Filling of container, measuring weight or water level

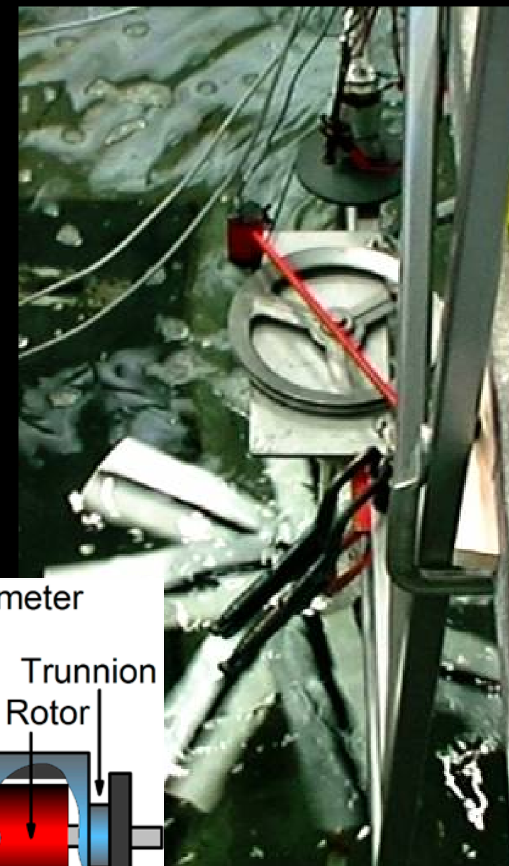




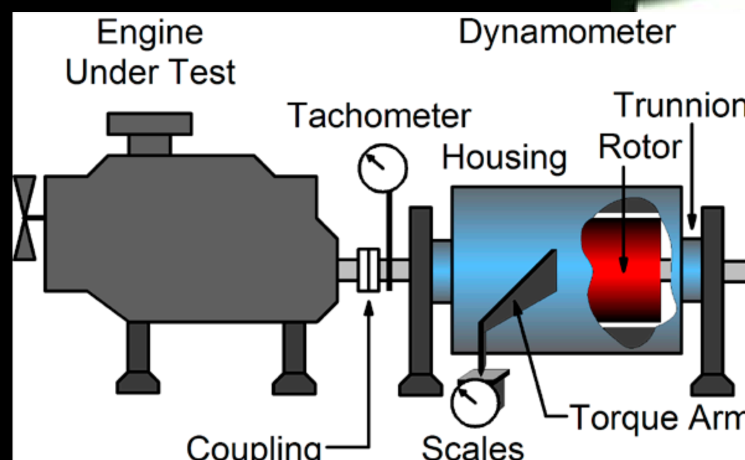




Torque – loading control



- Water breaks
- Disc brakes
- Dynamometer
- Weight in string on axle
- Generator



Modeling the power take-off system

Challenges

- Scaling the PTO normally does not follow the Froud scaling laws. Therefore, a direct model of the full scale PTO can not be used
- The load from the PTO feeds back to the hydraulic behavior of the device, and is normally of paramount importance for the performance of the device. Therefore, the load from the PTO on the system have to be controlable

Solutions

- In smaller scale, "just" model the loading from the PTO
- Measure the power production early in the power chain

Bevare of where in the chain of power you are measuring!

$$P_{wave} \Rightarrow P_{mech} \Rightarrow P_{hydr} \Rightarrow P_{axle} \Rightarrow P_{gen} \Rightarrow P_{wire} \Rightarrow P_{grid}$$

$$P_{overtop} \quad P_{reservoir}$$

$$P_{chamber} \quad P_{pneu}$$

Some examples – weights lifted by rotating axle

Power measured through weight, axle diameter, displacement and time

Pros

- Very simple and direct measurement. Easy to change loading – weights and/or axle diameter

Cons

- Limited test durations – need large heights for long tests. Therefore best for regular wave tests
- Not possible to change loading ”on the fly”
- Gives a constant torque on axle – not realistic loading charateristic of a generator

Some examples – friction force and velocity

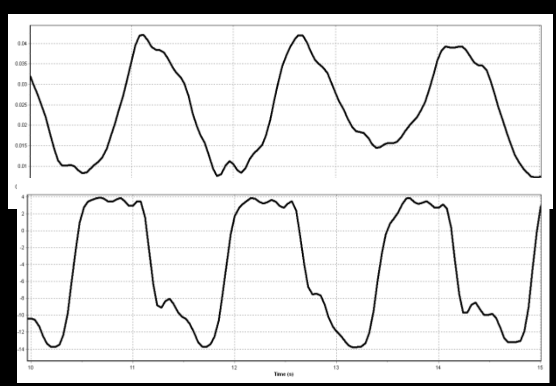
Power measured through force and
displacement time series

Pros

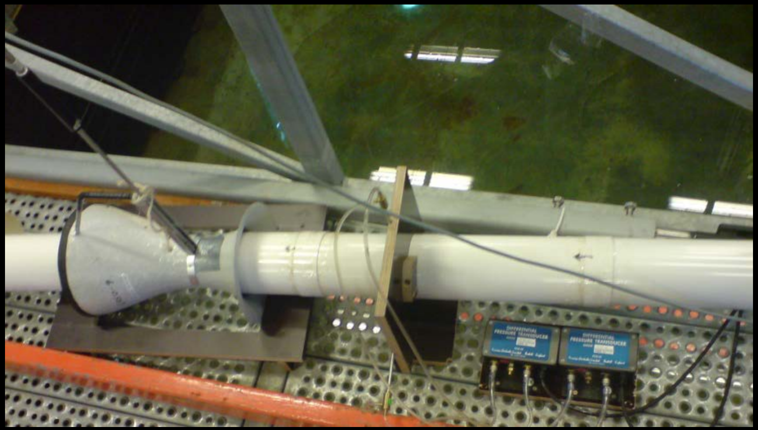
- No limitations on test duration
- Loading can in principle be changed ”on the fly”

Cons

- Risk of changing load characteristics due to heating of brakes
- Sometimes hard to get little enough friction for small waves



Some examples – air flow



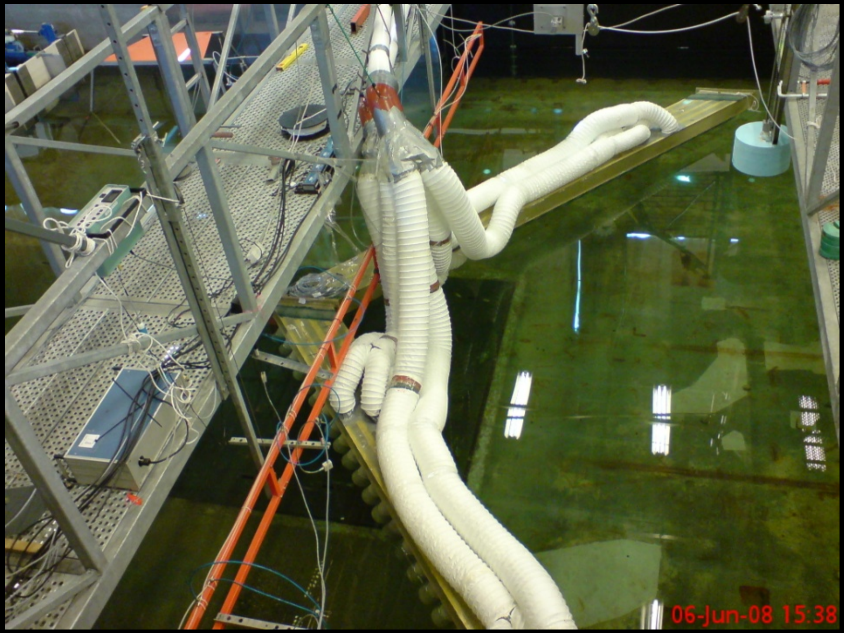
Power measured through flow and pressure time series

Pros

- Most appropriate for OWCs to get power measurements as early in the power chain as possible

Cons

- Difficulties in measuring fluctuating air flows



Some examples – overtopping flow

Power production measured through crest height and overtopping flow time series

Pros

- Simple and direct measurement
- Easy to change loading – crest height
- Power obtained very early in the power chain

Cons

- Resolution of flow in time
- Not possible to change loading "on the fly"
- Power obtained very early in the power chain

Some examples – Controllable force and velocity

Power production measured through force and velocity time series

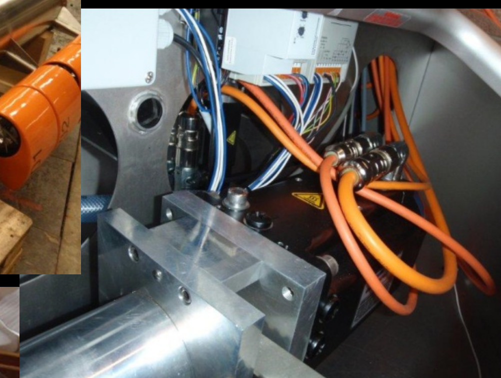
Pros

- Full control – can be run in force or displacement control mode

Cons

- Cost
- Complexity

Some examples – Controllable torque and rotational speed



Power production measured through torque and rotational velocity time series

Pros

- Full control – relation between torque and rotational velocity can be specified

Cons

- Cost
- Complexity

Scatter diagrams, power matrix...

- Load optimization

- Assumption on
  - max. generator capacity
  - level of active control
    - short term, wave to wave
    - longer term, sea state

Average power production estimated by multiplying (matrices)

Prob x Pwave x eff.

(Scatter Diagram x Power Matrix)

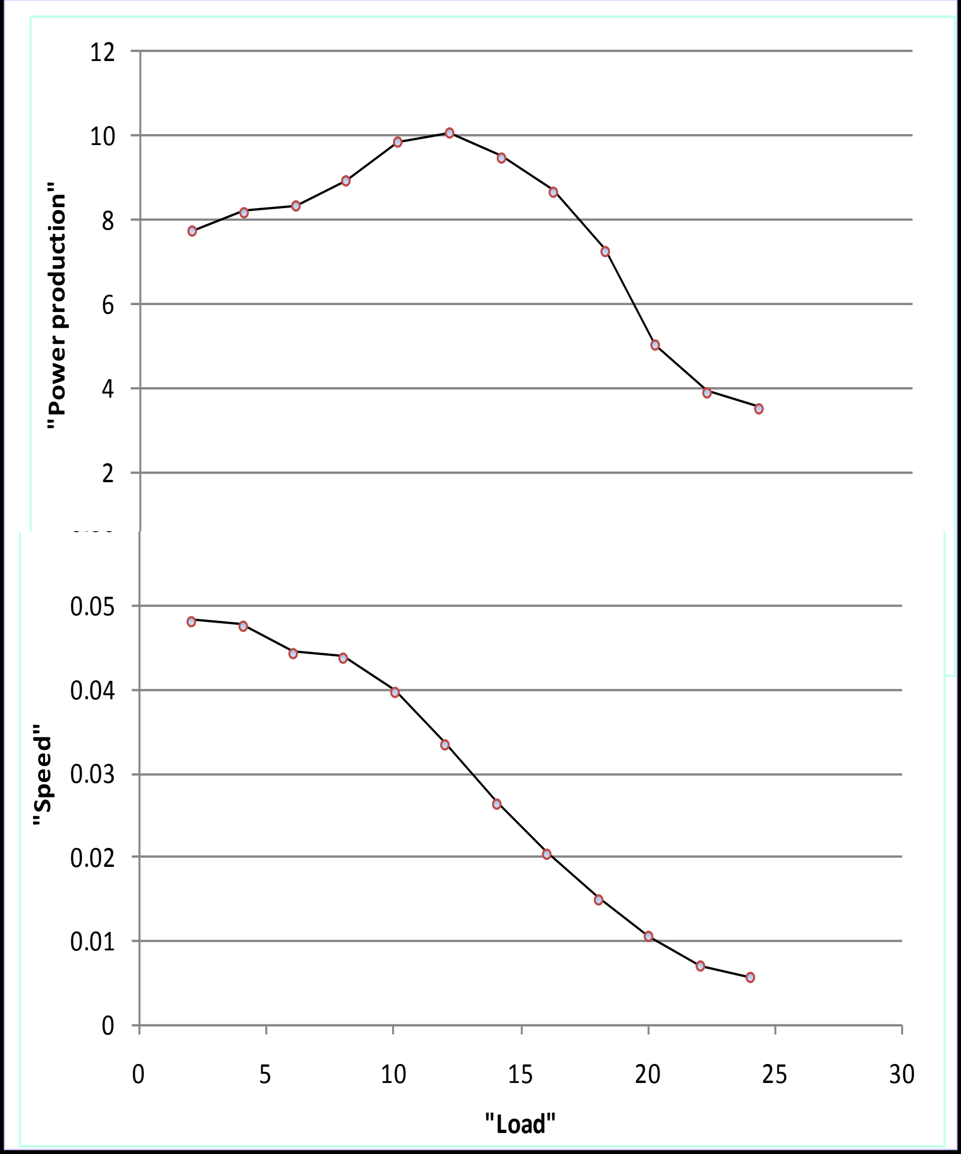
Load optimization

Often load optimized using regular waves (maintaining energy contents)

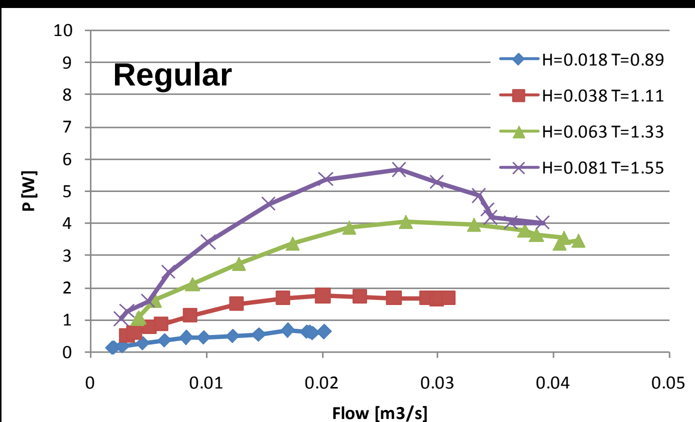
- H = Hm0/sqrt(2)
- T = Tp

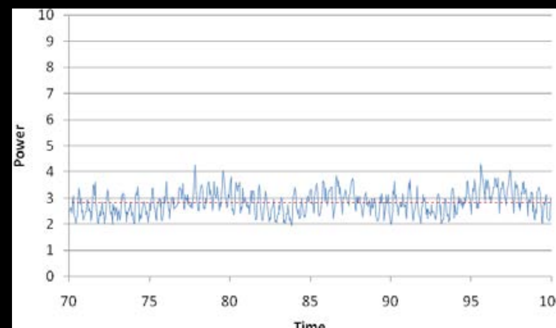
Optimization for each wave condition

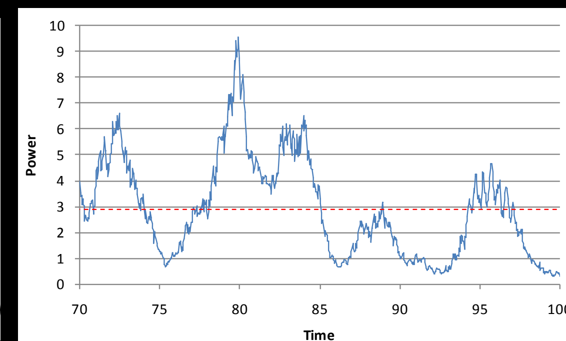
Power production measured in irregular waves using found optimal load setting (plus check runs on either sides)



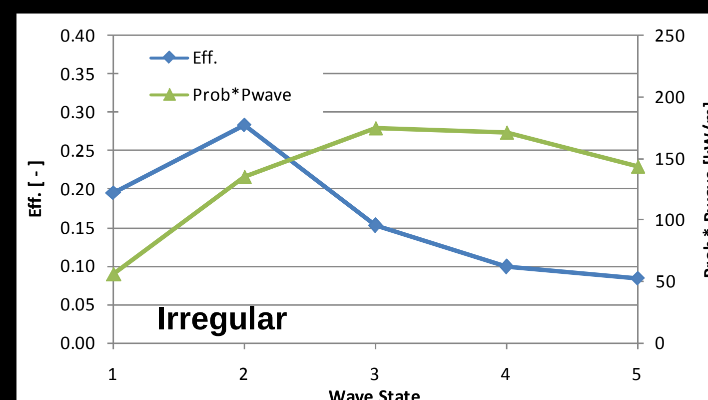
Estimation of yearly power production







Wave State	Pwave [kW]	Prob [%]	Prob*Pwave [kW]	Eff. [-]	Energy prod. [kW]	Pgen [kW]
1	120	0.468	56	0.195	11	23
2	598	0.226	135	0.284	38	170
3	1616	0.108	175	0.152	27	246
4	3351	0.051	171	0.098	17	330
5	5985	0.024	144	0.084	12	505
Yearly average [kW]			680		105	
Overall eff. [-]					0.154	
Yearly prod. [MWh/y]					919	
Max. Pgen [MW]						0.505
Load factor [-]						0.21



Energy production - exercise

Find Scatter Diagraam and Power Matrix for Wavestar in DropBox

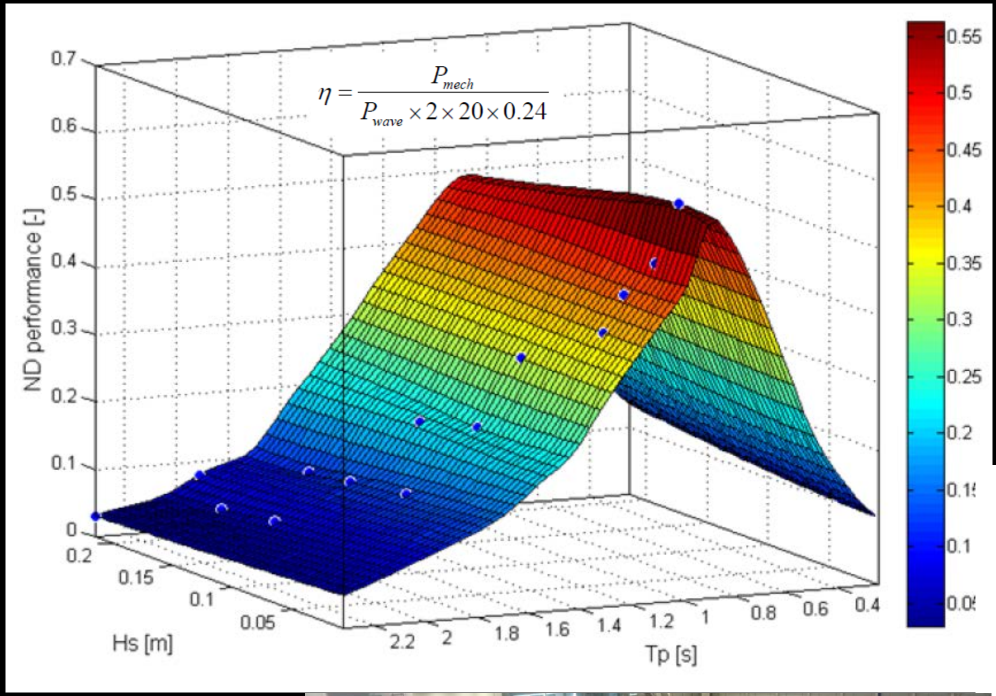
Assume the current Danish Feed-In-Tariff:

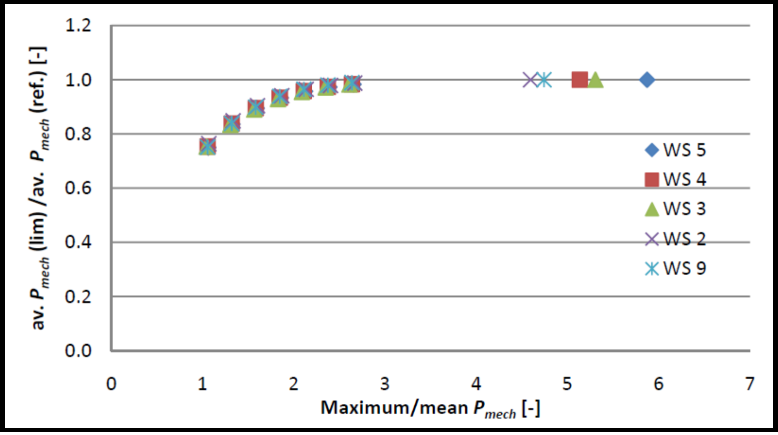
- 0.60 DKK/kWh first 10 years, 0.43 DKK/kWh hereafter

Calculate

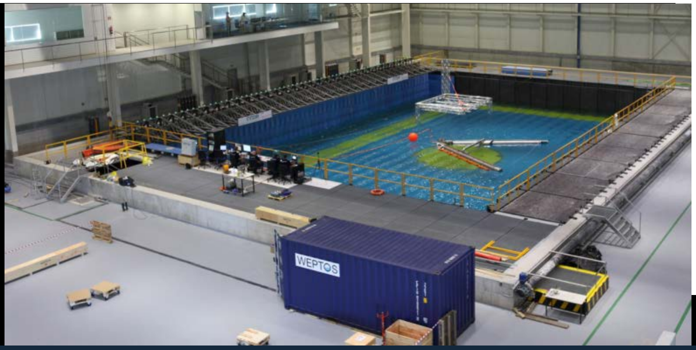
- Annual energy production (AEP [GWh/y])
- Total expectable income during 20 years [DKK]

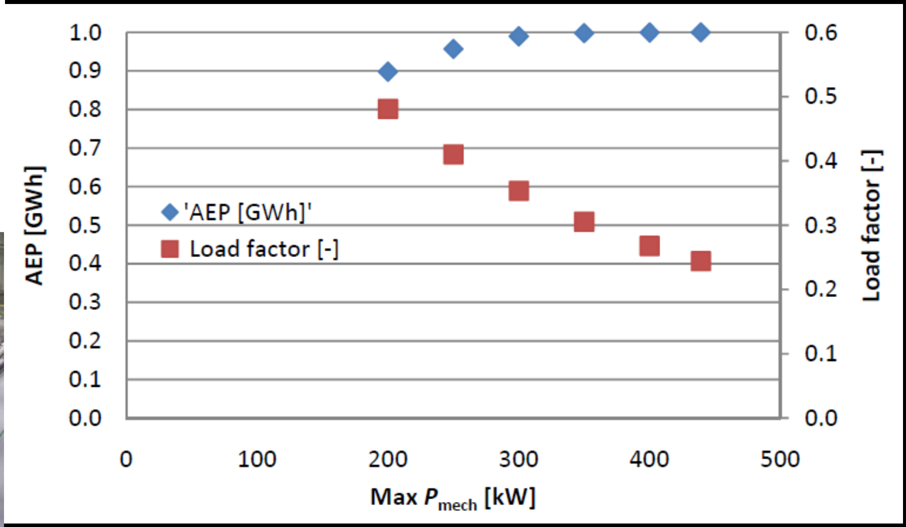
Power production measurements





Weptos





Anholt

Scaling ratio: 1.Relative to prototype 2. relative to reference	**8.33**		1.00		**10**		1.20		**12**		1.44		**15**		1.80	
Leg: 1.absolute length [m] 2.active length [m] 3.diameter [m]	63	40	2.9		76	48	3.5		91	58	4.2		114	72	5.3	
Rotor: 1.weight [ton] 2.volume [m^3] 3.width [m] 4.chord [m]	2.3	4.3	2.0	2.7	4.1	7.4	2.4	3.3	7.0	12.8	2.9	3.9	13.7	25.0	3.6	4.9
Pwave [kW/m]	0.99				0.99				0.99				0.99			
Load factor* [-] (unlimited and limited)	**0.13**	**0.32**	**0.40**	**0.51**	**0.11**	**0.32**	**0.39**	**0.48**	**0.09**	**0.30**	**0.37**	**0.45**	**0.08**	**0.30**	**0.36**	**0.44**
Maximum Pmech. [kW]	107	42	32	21	194	64	48	32	335	93	70	47	629	151	114	76
Overall η [-]	0.18	0.17	0.16	0.14	0.22	0.21	0.20	0.16	0.27	0.25	0.23	0.19	0.35	0.32	0.28	0.23
Average Pmech [kW]	14.1	13.6	12.7	10.8	21.2	20.1	18.5	15.4	31.1	28.5	25.7	21.1	50.5	45.0	40.5	33.2
Annual Energy Production [GWh]	0.12	0.12	0.11	0.09	0.18	0.17	0.16	0.13	0.27	0.25	0.22	0.18	0.44	0.39	0.35	0.29
Relative AEP to unlimited load factor [-]	1.0	0.97	0.90	0.77	1.0	0.95	0.87	0.73	1.0	0.91	0.83	0.68	1.0	0.89	0.80	0.66
Relative AEP to reference [-]	1.00	0.97	0.90	0.77	1.51	1.43	1.31	1.09	2.21	2.02	1.83	1.50	3.59	3.20	2.88	2.36

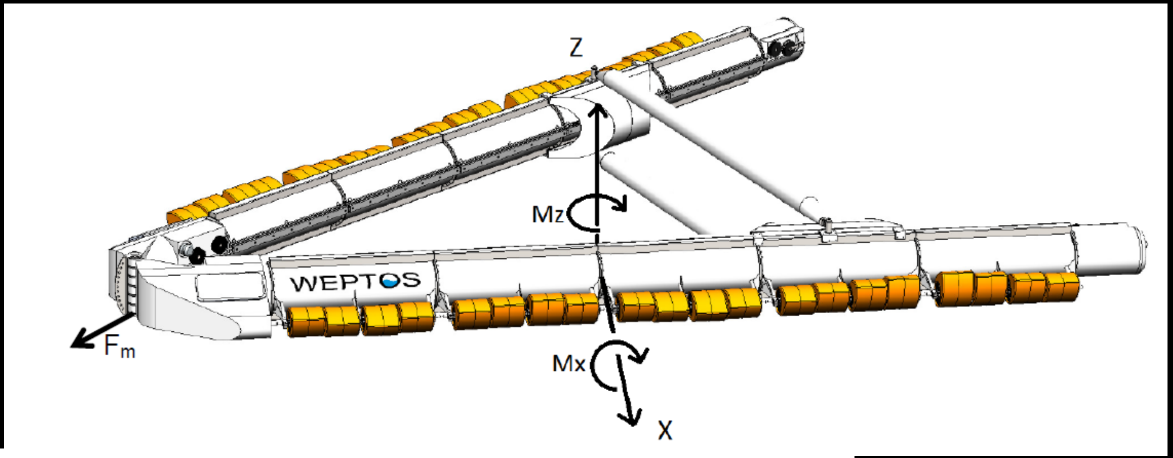
Hanstholm (DanWEC)

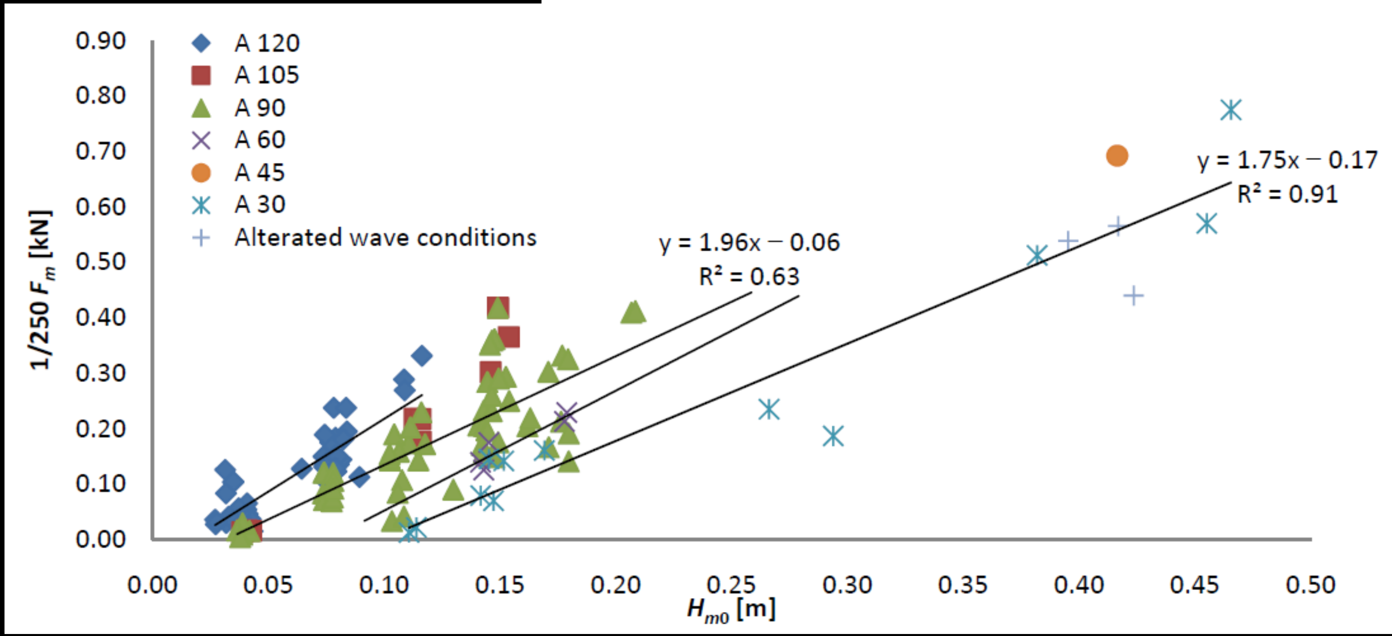
Scaling ratio: 1.Relative to prototype 2. relative to reference	**12**		1.0		**15**		1.25		**20**		1.67		**25**		2.08	
Leg: 1.absolute length [m] 2.active length [m] 3.diameter [m]	91	58	4.2		114	72	5.3		152	96	7.1		190	120	8.9	
Rotor: 1.weight [ton] 2.volume [m^3] 3.width [m] 4.chord [m]	7	13	2.9	3.9	14	25	3.6	4.9	32	59	4.8	6.5	63	115.7	6.0	8.2
Pwave [kW/m]	6.1				6.1				6.1				6.1			
Load factor* [-] (unlimited and limited)	**0.08**	**0.33**	**0.42**	**0.55**	**0.08**	**0.33**	**0.42**	**0.54**	**0.06**	**0.32**	**0.41**	**0.52**	**0.06**	**0.32**	**0.39**	**0.50**
Maximum Pmech. [kW]	757	176	132	88	1454	330	247	165	3656	699	524	349	6017	1166	875	583
Overall η [-]	0.08	0.08	0.08	0.07	0.12	0.12	0.12	0.10	0.20	0.19	0.18	0.15	0.26	0.25	0.23	0.20
Average Pmech [kW]	59	58	56	48	110	108	103	89	233	226	213	183	389	370	344	293
Annual Energy Production [GWh]	0.5	0.5	0.5	0.4	1.0	0.9	0.9	0.8	2.0	2.0	1.8	1.6	3.4	3.2	3.0	2.5
Relative AEP to unlimited load factor [-]	1.0	0.99	0.95	0.82	1.0	0.99	0.94	0.81	1.0	0.97	0.91	0.78	1.0	0.95	0.89	0.75
Relative AEP to reference [-]	1.0	0.99	0.95	0.82	1.87	1.85	1.76	1.52	3.97	3.86	3.63	3.11	6.63	6.31	5.87	4.99

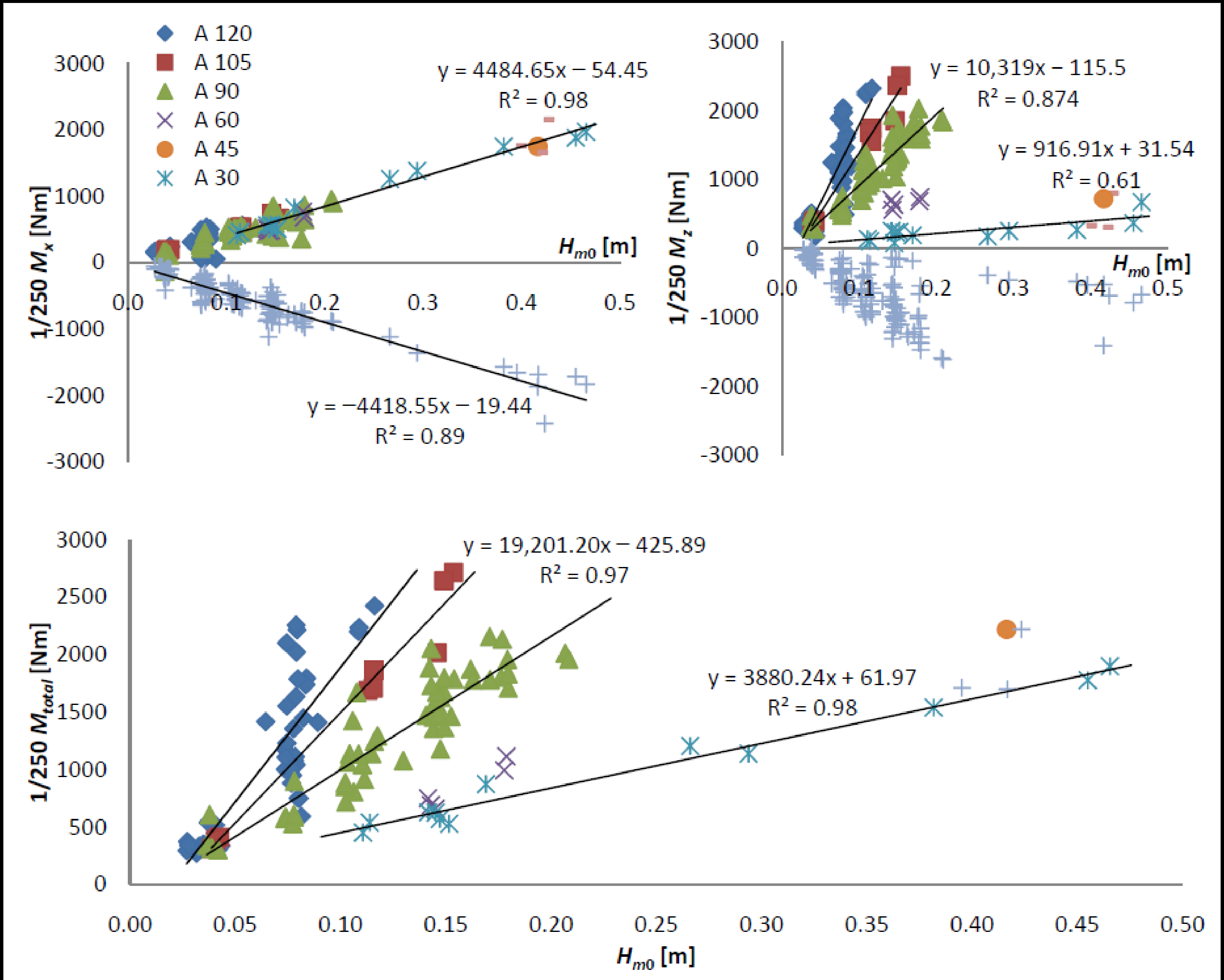
Danish part of the North Sea

Scaling ratio: 1.Relative to prototype 2. relative to reference	**23.4**				**25**				**30**				**35**			
Leg: 1.absolute length [m] 2.active length [m] 3.diameter [m]	178	112	8.3		190	120	8.9		228	144	10.6		266	168	12.4	
Rotor: 1.weight [ton] 2.volume [m^3] 3.width [m] 4.chord [m]	52	95	5.6	7.6	63	116	6.0	8.2	110	200	7.2	9.8	174	317.6	8.4	11.4
Pwave [kW/m]	16.3				16.3				16.3				16.3			
Load factor* [-] (unlimited and limited)	**0.18**	**0.33**	**0.42**	**0.55**	**0.19**	**0.33**	**0.42**	**0.54**	**0.18**	**0.33**	**0.41**	**0.52**	**0.16**	**0.32**	**0.39**	**0.49**
Maximum Pmech. [kW]	2080	1147	860	574	2422	1368	1026	684	4126	2196	1647	1098	6627	3152	2364	1576
Overall η [-]	0.10	0.10	0.10	0.09	0.12	0.12	0.11	0.09	0.16	0.15	0.14	0.12	0.19	0.19	0.17	0.14
Average Pmech [kW]	382	379	363	315	456	452	430	370	732	721	677	573	1051	1012	933	780
Annual Energy Production [GWh]	3.3	3.3	3.1	2.7	4.0	3.9	3.7	3.2	6.3	6.2	5.9	5.0	9.1	8.8	8.1	6.8
Relative AEP to unlimited load factor [-]	1.0	0.99	0.95	0.82	1.0	0.99	0.94	0.81	1.0	0.98	0.92	0.78	1.0	0.96	0.89	0.74
Relative AEP to reference [-]	1.00	0.99	0.95	0.82	1.19	1.18	1.12	0.97	1.91	1.89	1.77	1.50	2.75	2.65	2.44	2.04

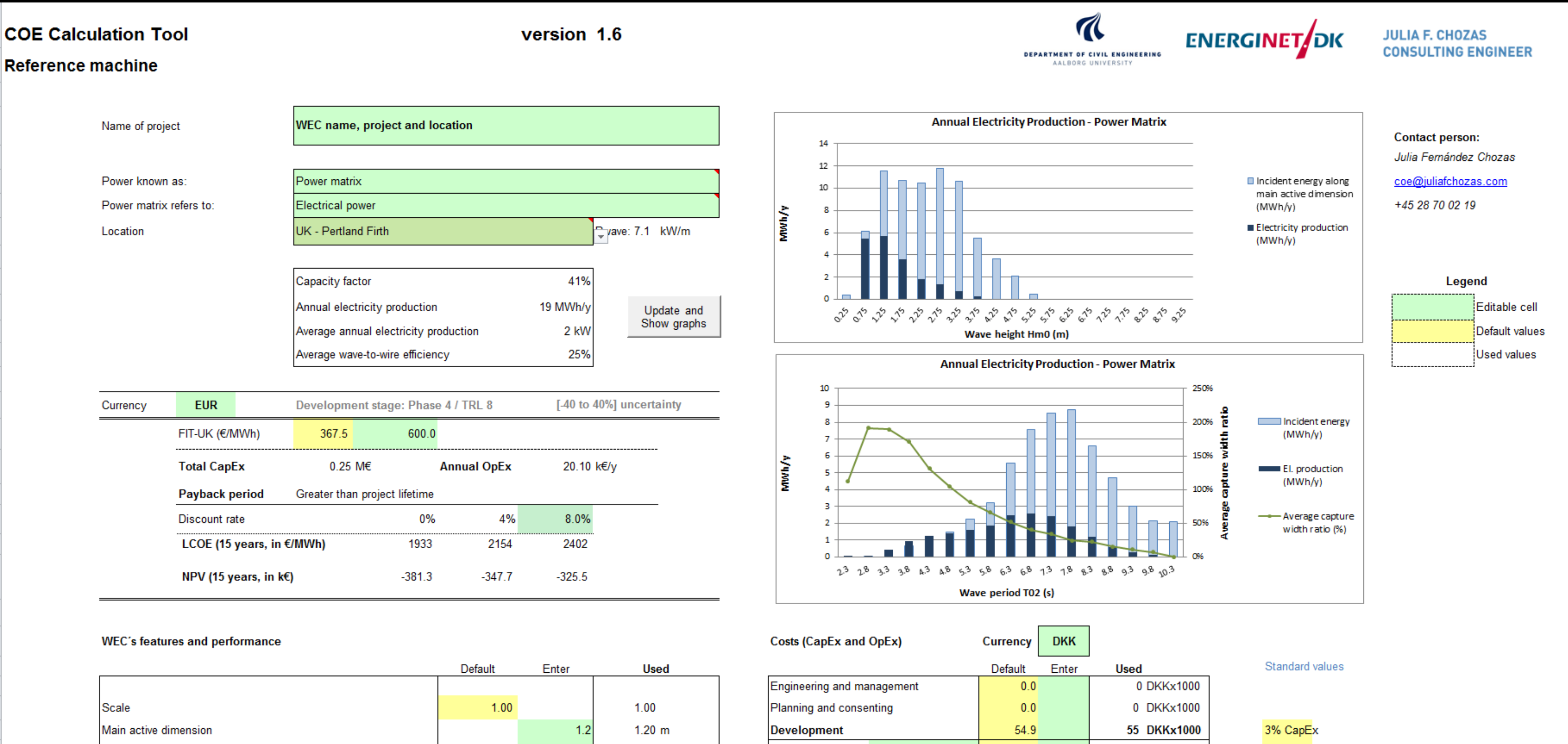
Loadings


Z
Mz
WEPTOS
Fm
Mx
X


A 120
A 105
A 90
A 60
A 45
A 30
Alterated wave conditions
y = 1.96x − 0.06
R² = 0.63
y = 1.75x − 0.17
R² = 0.91
1/250 Fm [kN]
Hm0 [m]
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
0.05
0.15
0.25
0.35
0.45


A 120
A 105
A 90
A 60
A 45
A 30
y = 4484.65x − 54.45
R² = 0.98
y = −4418.55x − 19.44
R² = 0.89
1/250 M_x [Nm]
H_{m0} [m]
y = 10,319x − 115.5
R² = 0.874
y = 916.91x + 31.54
R² = 0.61
1/250 M_z [Nm]
H_{m0} [m]
y = 19,201.20x − 425.89
R² = 0.97
y = 3880.24x + 61.97
R² = 0.98
1/250 M_{total} [Nm]
H_{m0} [m]

COE Calculation spreadsheet



COE sheet

http://vbn.aau.dk/en/publications/user-guide--coe-calculation-tool-for-wave-energy-converters(78b135d9-ea66-43f8-959f-c799dc4df1a9).html

Shortcomings of SD/PM approach

- Resolution
- Linear interpolation
- Standard spectral shape
- Constant bin size
- More dimensions (direction, water level, …)
- Limited data sets

- See more e.g.
  - Andres Gutierrez, AD 2015, 'Finding gaps on techno-economic assessment on Wave Energy Converters: path towards commercialization'. PhD thesis, University of Cantabria
  - Lavelle, J & Kofoed, JP 2013, 'Representative spectra of the wave resource from real sea wave measurements'. in Proc. 10th EWTEC, Aalborg.
  - Kofoed, JP et al. 2013, 'A Methodology for Equitable Performance Assessment and Presentation of Wave Energy Converters Based on Sea Trials' Renewable Energy, vol 52, no. April, pp. 99-110., 10.1016/j.renene.2012.10.040

AALBORG UNIVERSITET

Questions - comments?

Thank you!